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Coherent tunneling by adiabatic process in a four-waveguide optical coupler

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ABSTRACT

We numerically simulate Schrödinger-like paraxial wave equation of a four-waveguide system. The coherent tunneling by adiabatic passage in a four-waveguide optical coupler is analyzed by borrowing the dressed state theory of coherent atom system. We discuss the optical coupling mechanism and coupling efficiency of light energy in both intuitive and counterintuitive tunneling schemes and analyze the threshold condition from adiabatic to non-adiabatic regimes in intuitive scheme. The results show that this coupler can be used as power splitter under certain conditions.

1. Introduction

Although equations that describe the dynamics in quantum and classical physics are different, there are many similarities between quantum and classical physical phenomena [1]. These analogies have been exploited to mimic microscopic quantum effect at macroscopic level, including using engineered photonic structures to mimic Zener tunneling [2] and quantum effects such as Bloch oscillations [3]; using waveguide directional coupler to mimic the generation of discrete solitons [4], Aharonov–Bohm effect [5], Bloch oscillations [6], discrete Talbot effect [7], adiabatic mode conversion [8,9], Landau–Zener dynamics [10], Stimulated Raman adiabatic passage (STIRAP) [11,12], to name a few.

As an important tool which can manipulate the quantum structures, STIRAP is widely used in coherent atomic excitation [13,14], optical switching [15], quantum information processing [16], waveguide optics [12,17,18], generation of short terahertz pulses [19], etc. STIRAP is based on the dark state of the system. In a three-waveguide optical coupler, the coherent tunneling adiabatic passage is based on the existence of one dark state[11]; in a four-waveguide optical coupler, however, this adiabatic passage is base on the existence of two dark states, which is the linear superposition of the initial and target states. In 2012, Xin–Ding Zhang group discussed the non-Abelian geometric phase and the light energy adiabatic passage in a four-waveguide system which is composed of a central straight waveguide, a similar parabolic waveguide and two cosine-type waveguides [20]. In 2015, this group further discussed the Abelian geometric phase in a waveguide system which is composed of a central straight waveguide and three similar parabolic waveguides [21]. But they only discussed the structure in counterintuitive tunneling scheme, failing to elaborate on the adiabatic condition, the adiabatic conversion efficiency versus the distance between the upper and central waveguide, and the way to obtain adiabatic conversion condition in intuitive tunneling scheme.

In this paper we discuss a four-waveguide coupler which is composed of two straight waveguides and two similar parabolic waveguides. The central and upper waveguide are straight, the left and right waveguide are similar parabolic. By analogy to the STIRAP of the four level atoms, the coherent tunneling in a four-waveguide coupler is studied, progress in theoretical and experimental studies of multi waveguide array couplers can assure the rationality of the waveguide characteristic parameters selected in this paper [11,22]. When light is introduced from the left waveguide, the left waveguide is coupled with the center waveguide before the right one, therefore creating the intuitive tunneling scheme. On the other hand, when the right waveguide is coupled with the center waveguide before the left one, the counterintuitive tunneling scheme is created. By using the theory of dressed state we analyze the dynamic process of the energy adiabatic transfer in a four-waveguide coupler, discussing the energy coupling efficiency and adiabatic conditions in different tunneling rate scheme. The upper waveguide is straight, so such coupler is more easily to be manufactured than the structure in reference [21] and can be used as power splitter under certain conditions.

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2. Theoretical modeling

Waveguide structures are shown in Fig. 1(a). The left waveguide (L) and the right waveguide (R) are similar parabolic, which are located in the YZ plane with the central straight waveguide (C), the upper straight waveguide (U) and the central waveguide in the XZ plane. Light propagates along the z direction. Direct tunneling among the left, right and upper channels can be fully ignored because of their far distance. They can only be coupled with the intermediate waveguide. The refractive index profile $n_w(X, Y)$ of the waveguide is the same as in reference [11]. Fig. 1(b) is a section of the four waveguide coupler in the XY plane. Ω_s, Ω_p and Ω_q are the tunneling rate between the adjacent waveguide. The four set of contour lines is the distribution of the refractive index function in the XY plane of the four waveguides.

The monochromatic light propagating in the waveguide directional coupler along Z direction can be described by Schrödinger-like paraxial wave equation [11]

$$i\hbar\frac{\partial\psi}{\partial Z} = -\frac{\hbar^2}{2n_s}\nabla^2_{X,Y}\psi + V(X - X_0(Z), Y - Y_0(Z))\psi \tag{1}$$

In Eq. (1), $\hbar = \lambda/(2\pi)$ is reduced wavelength, $V(X, Y, Z)$ is spatial potential distribution function,

$$V(X, Y, Z) = [n_s^2 - n^2(X, Y, Z)]/(2n_s) \approx n_s - n(X, Y, Z),$$

n_s is substrate refractive index, $n(X, Y, Z)$ is the refractive distribution of four-waveguide directional coupler, $|\psi|^2$ denotes the beam intensity in the coupler.

By introducing new variables, $x = X - X_0$, $y = Y - Y_0$, $z = Z$, after the gauge transformation:

$$\psi = \phi\ \exp\left\{ i(n_s/\hbar)[\dot{X}_0(Z)x + \dot{Y}_0(Z)y] + i(n_s/2\hbar)\int^Z d\xi\left[\dot{X}_0^2(\xi) + \dot{Y}_0^2(\xi)\right]\right\},$$

$\dot{X}_0$, $\dot{Y}_0$ indicates the derivative with respect to z, and substitute the new variables into Eq. (1), we can get:

$$i\hbar\frac{\partial\phi}{\partial z} = H\phi \tag{2}$$

The Hamiltonian $H = H_0 + H'$, where $H_0 = -\frac{\hbar^2}{2n_s}\nabla^2_{x,y} + V(x, y)$, $H' = n_s\left[\ddot{X}_0(z)\hat{e}_x + \ddot{Y}_0(z)\hat{e}_y\right]\cdot\vec{r}$,

if we expand the state vector $\phi(x, y, z)$ as the linear superposition of the basis vector $w_n(x, y)$.

$$\phi(x, y, z) = \sum_n C_n(z)\exp(-i\omega_n z)w_n(x, y) \tag{3}$$

and substitute Eq. (3) into Eq. (2), under the general hypotheses of nearest-neighbor approximation and weak waveguide coupling, we get:

$$\frac{d}{dz}C(z) = -iW(z)C(z) \tag{4}$$

where we have set

$$W(z) = \begin{pmatrix} 0 & \Omega_p(z) & 0 & 0 \\ \Omega_p^*(z) & 0 & \Omega_s(z) & \Omega_q(z) \\ 0 & \Omega_s^*(z) & 0 & 0 \\ 0 & \Omega_q^*(z) & 0 & 0 \end{pmatrix} \tag{5}$$

The state vector $C(z) = [C_L(z), C_C(z), C_R(z), C_U(z)]^T$ is complex amplitude of light field in four waveguides. $|C_n(z)|^2$ indicates the variation of beam intensity with the propagating distance z in the four waveguides. $\Omega_i(z)\,(i = p, s, q)$ is the tunneling rate between the adjacent waveguide.

Eq. (4) shows the propagation of light in a four-waveguide coupler system, which is similar to the STIRAP occurring in the interaction between the three pulsed laser fields and a four-state atomic system. The Rabi frequency of the pump pulse and Stokes pulse correspond to the tunneling rate between the adjacent waveguides, when light comes from the left waveguide in intuitive tunneling scheme ($\delta < 0$), or in counterintuitive tunneling scheme ($\delta > 0$). The eigenvalue of the tunneling rate matrix are: $\lambda_1(z) = \lambda_2(z) = 0$, $\lambda_3(z) = -\Omega_0(z)$ $\lambda_4(z) = +\Omega_0(z)$, $\Omega_0(z) = \sqrt{|\Omega_p(z)|^2 + |\Omega_s(z)|^2 + |\Omega_q(z)|^2}$. The two null-eigenvalues are degenerated, STIRAP occurs in these two dark states.

Defining the distance-dependent mixing angle $\theta(z)$ and $\varphi(z)$ as

$$\tan\theta(z) = \frac{|\Omega_p(z)|}{|\Omega_s(z)|} \tag{6}$$

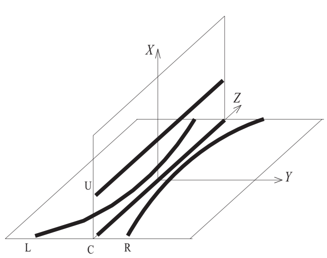
$$\tan\varphi(z) = \frac{|\Omega_q(z)|}{\sqrt{|\Omega_p(z)|^2 + |\Omega_s(z)|^2}} \tag{7}$$

The eigenvectors of the dressed state are

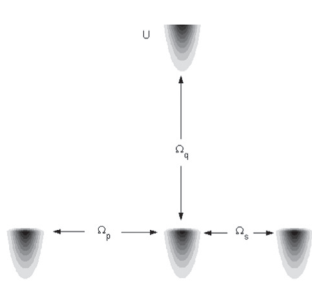
$$\Phi_1(z) = \begin{pmatrix} \cos\theta(z) \\ 0 \\ -\sin\theta(z) \\ 0 \end{pmatrix} \quad \Phi_2(z) = \begin{pmatrix} \sin\varphi(z)\sin\theta(z) \\ 0 \\ \sin\varphi(z)\cos\theta(z) \\ -\cos\varphi(z) \end{pmatrix} \tag{8}$$

$$\Phi_3(z) = \frac{1}{\sqrt{2}}\begin{pmatrix} \cos\varphi(z)\sin\theta(z) \\ -1 \\ \cos\varphi(z)\cos\theta(z) \\ \sin\varphi(z) \end{pmatrix} \quad \Phi_4(z) = \frac{1}{\sqrt{2}}\begin{pmatrix} \cos\varphi(z)\sin\theta(z) \\ 1 \\ \cos\varphi(z)\cos\theta(z) \\ \sin\varphi(z) \end{pmatrix} \tag{9}$$

In the adiabatic limit, $d\theta(z)/dz$ and $d\varphi(z)/dz$ are both small, the non-adiabatic coupling of dark states Φ_1 or Φ_2 to the dress states Φ_3 or Φ_4 can be ignored. If the system is initially in a dark state, it



(a). Schematic of the four-waveguide directional coupler.



(b). Refractive index profile $n_w(X,Y)$ of the waveguide and the tunneling pattern between different waveguide.

Fig. 1. (a) Schematic of the four-waveguide directional coupler. (b) Refractive index profile $n_w(X, Y)$ of the waveguide and the tunneling pattern between different waveguide.